Kentucky Electricity Portfolio Model

Developed by

Kentucky Energy and Environment Cabinet

Department for Energy Development Independence

In Partnership with

University of Kentucky Department of Statistics

University of Kentucky Center for Applied Energy Research

Pacific Northwest National Laboratory

May 13th, 2014

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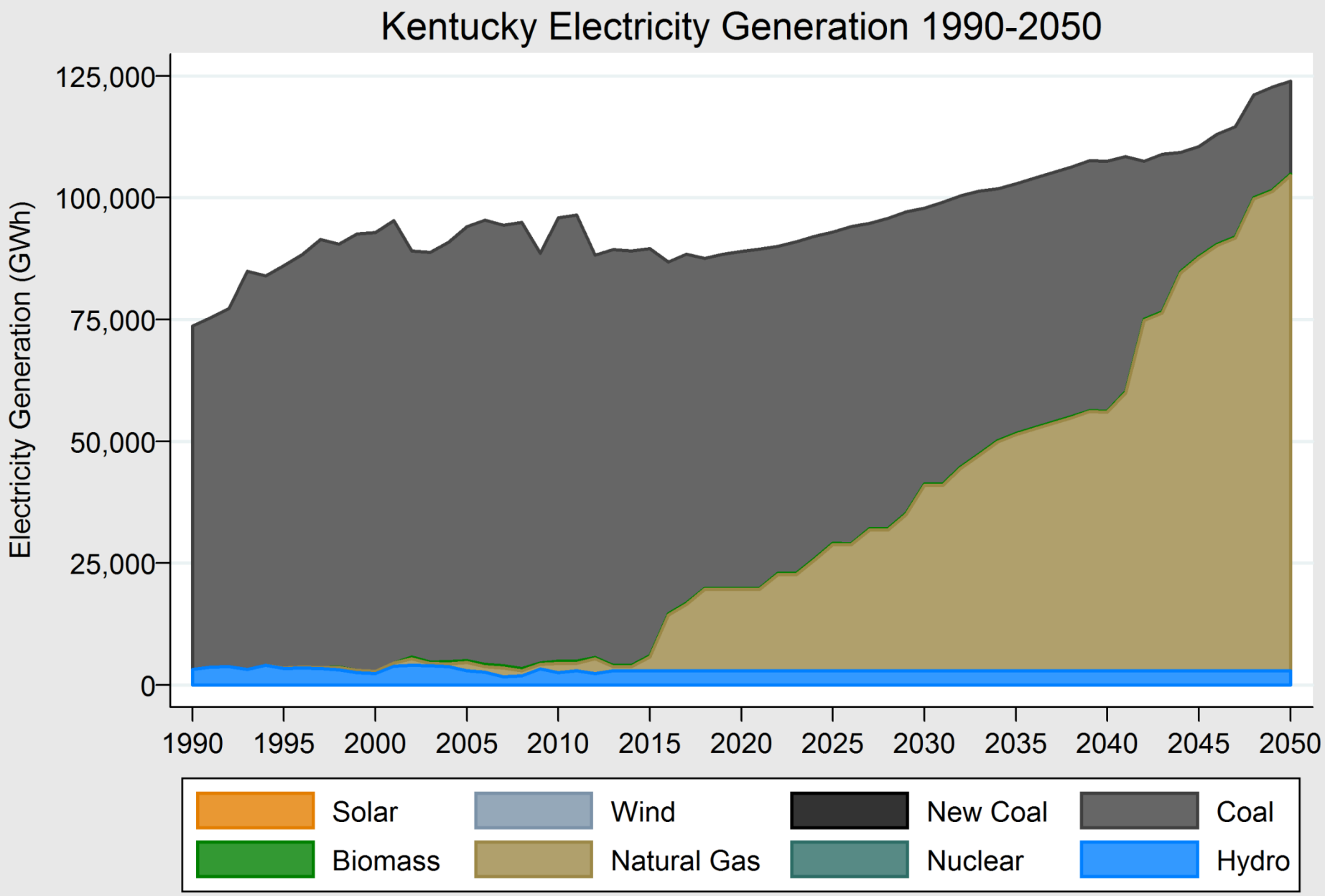
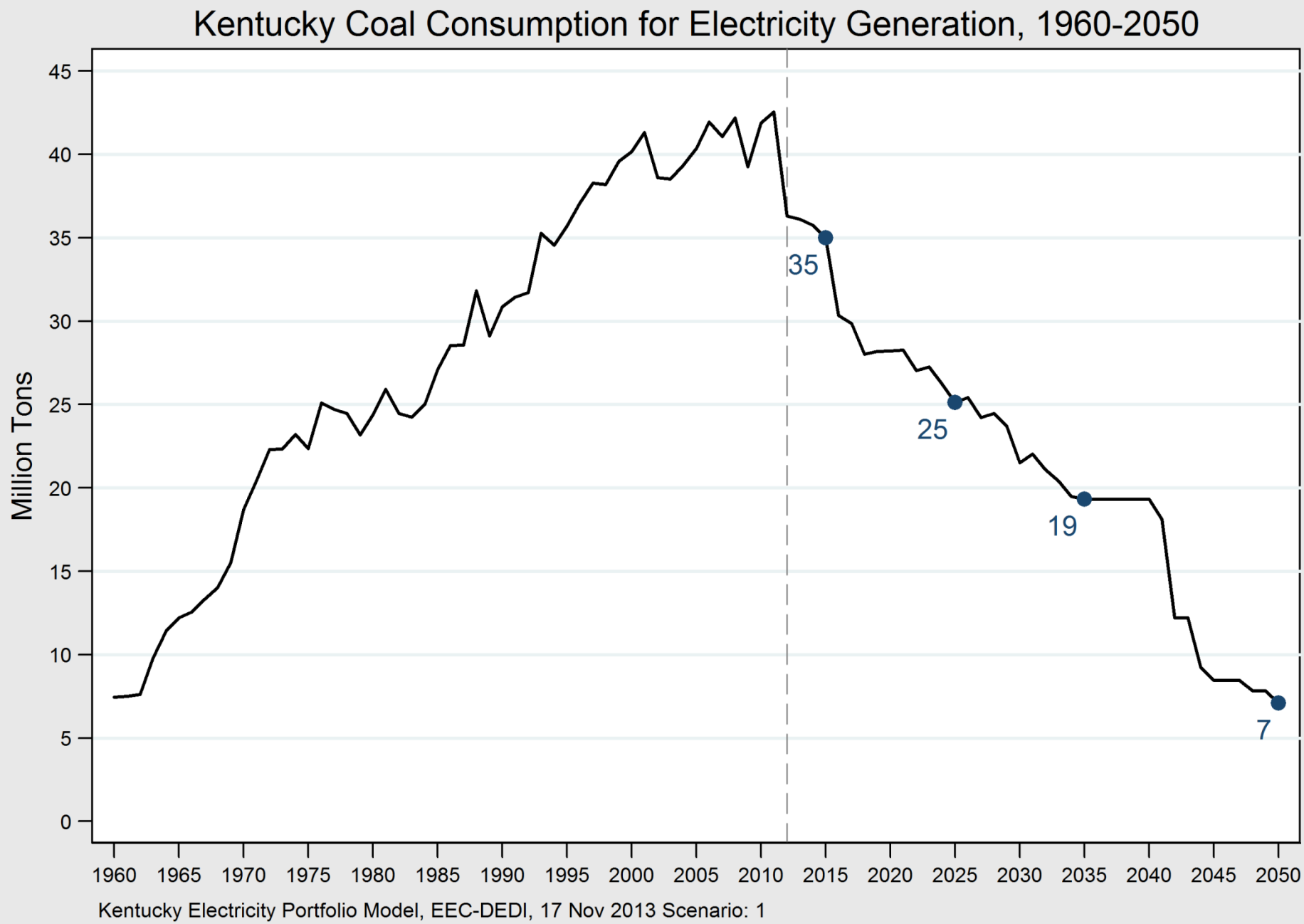
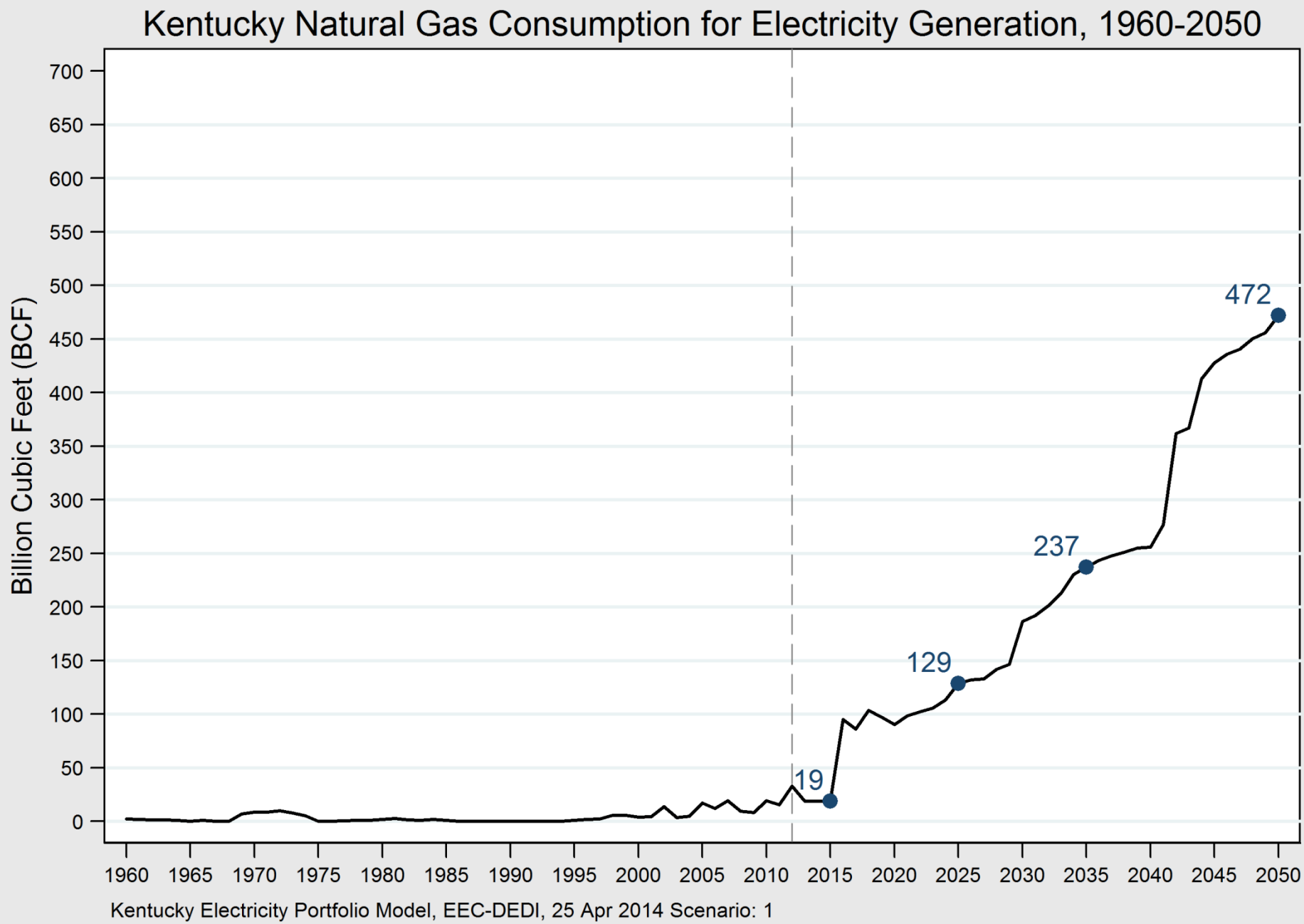
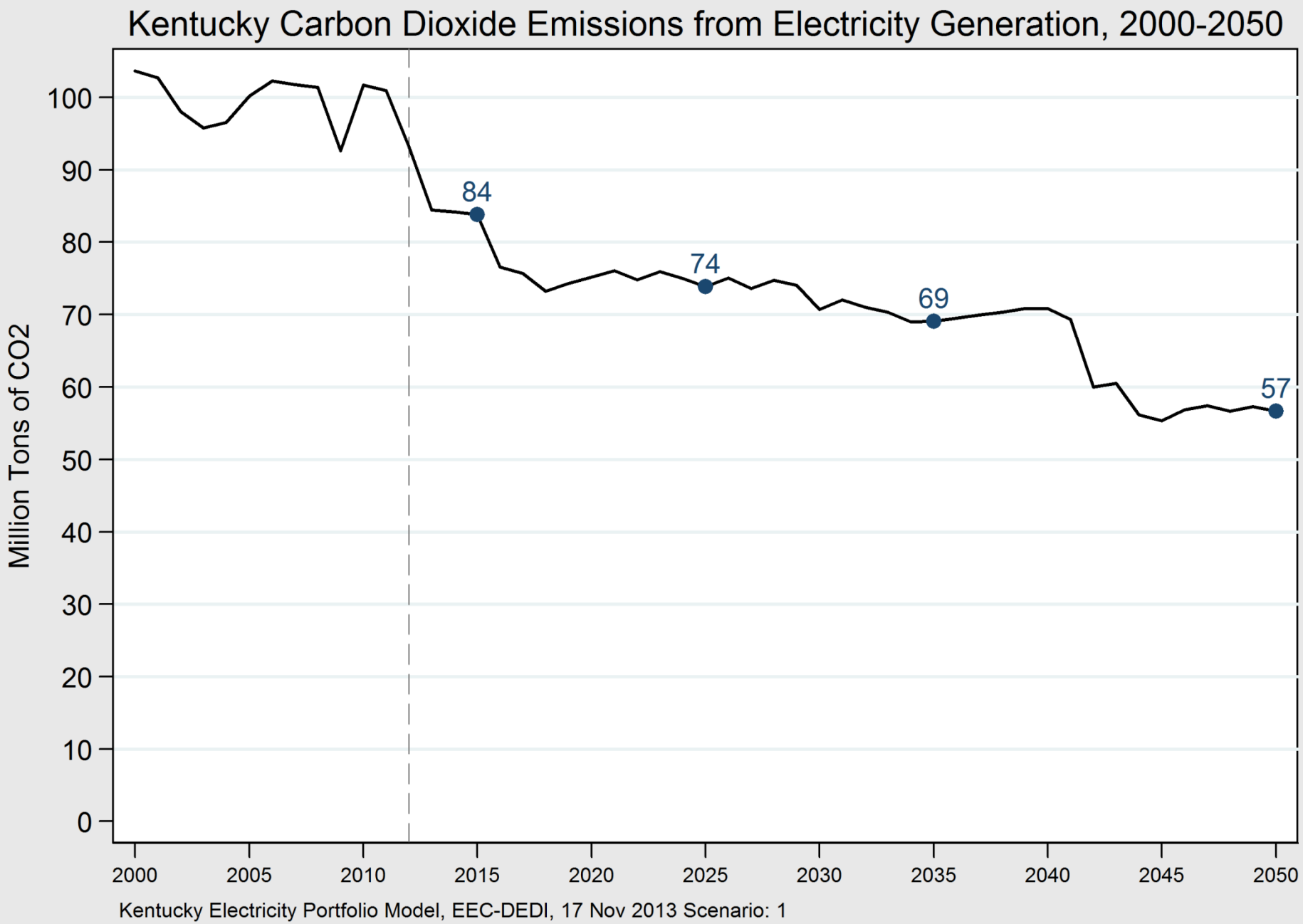
"Economic Challenges Facing Kentucky's Electricity Generation Under Greenhouse Gas Constraints"


Kentucky Electricity Generation 1990-2050
Electricity Generation (GWh)
125,000
100,000
75,000
50,000
25,000
0
1990
1995
2000
2005
2010
2015
2020
2025
2030
2035
2040
2045
2050
Solar
Wind
New Coal
Coal
Biomass
Natural Gas
Nuclear
Hydro
Kentucky Electricity Portfolio Model, EEC-DEDI, 17 Nov 2013 Scenario:1


Kentucky Coal Consumption for Electricity Generation, 1960-2050
Million Tons
45
40
35
30
25
20
15
10
5
0
1960
1965
1970
1975
1980
1985
1990
1995
2000
2005
2010
2015
2020
2025
2030
2035
2040
2045
2050
35
25
19
7
Kentucky Electricity Portfolio Model, EEC-DEDI, 17 Nov 2013 Scenario: 1


Kentucky Natural Gas Consumption for Electricity Generation, 1960-2050
Billion Cubic Feet (BCF)
700
650
600
550
500
450
400
350
300
250
200
150
100
50
0
472
237
129
19
1960
1965
1970
1975
1980
1985
1990
1995
2000
2005
2010
2015
2020
2025
2030
2035
2040
2045
2050
Kentucky Electricity Portfolio Model, EEC-DEDI, 25 Apr 2014 Scenario: 1


Kentucky Carbon Dioxide Emissions from Electricity Generation, 2000-2050
Million Tons of CO2
100
90
80
70
60
50
40
30
20
10
0
84
74
69
57
2000
2005
2010
2015
2020
2025
2030
2035
2040
2045
2050
Kentucky Electricity Portfolio Model, EEC-DEDI, 17 Nov 2013 Scenario: 1

A Quick Introduction to

Kentucky Electricity Portfolio Model

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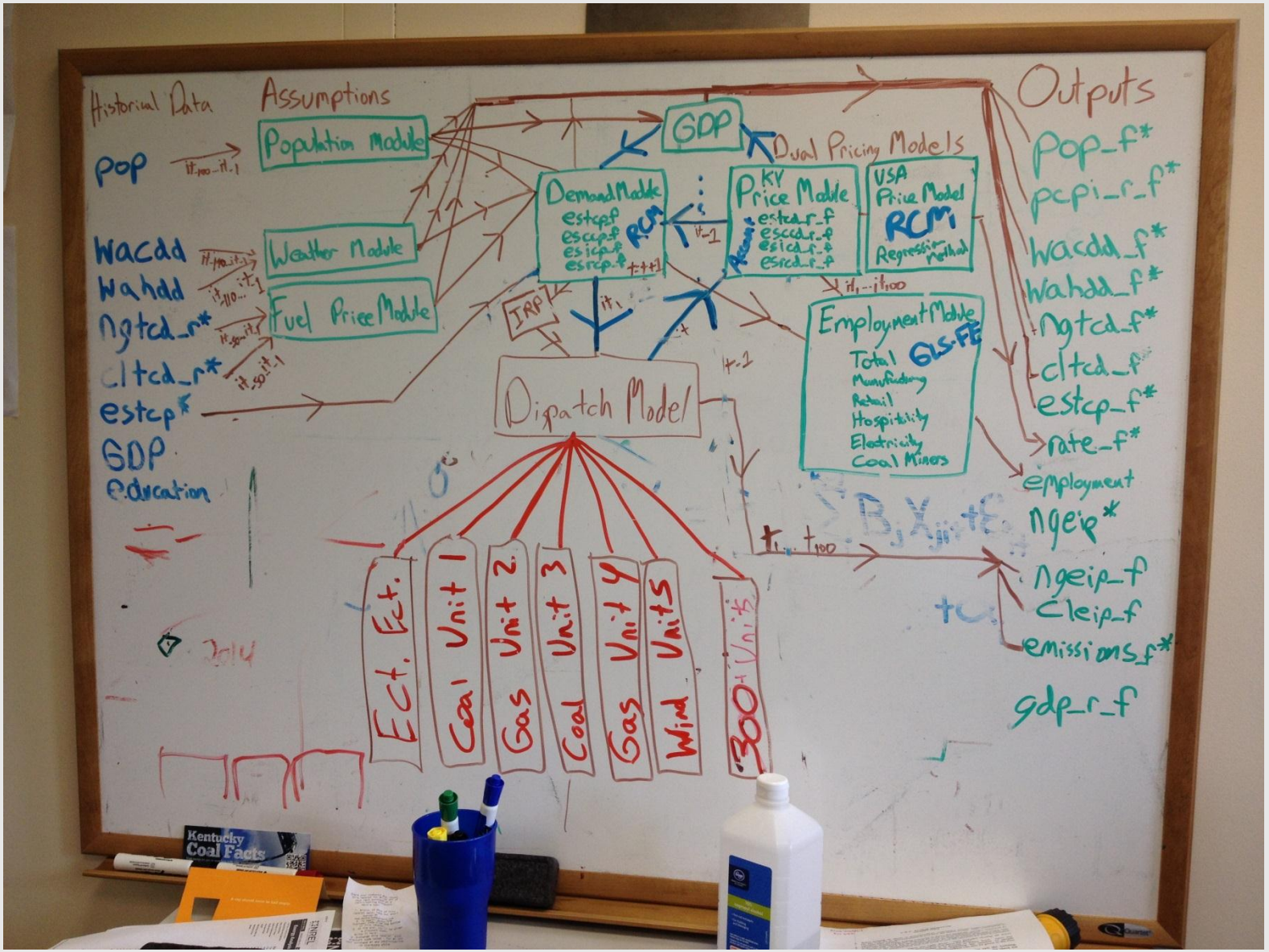
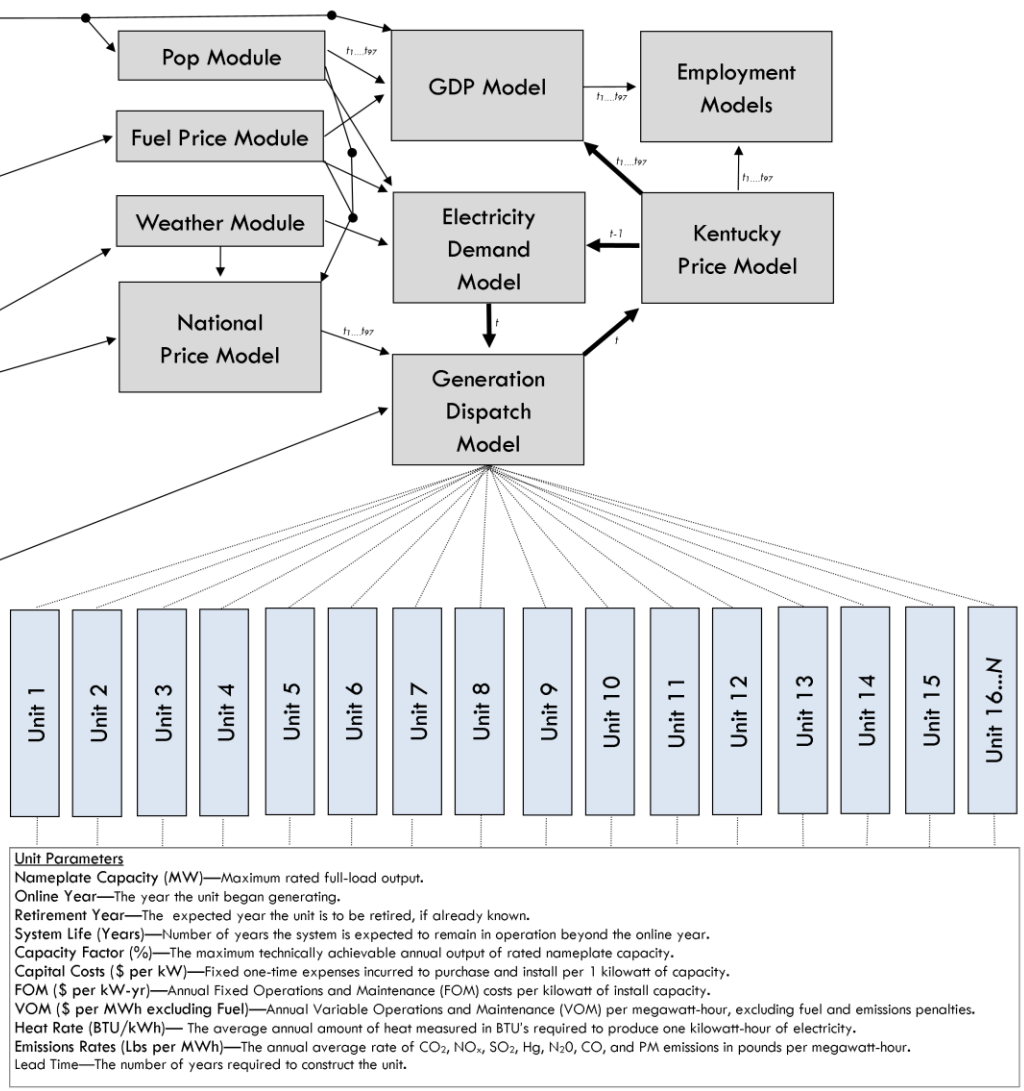
Original Model Design Plan



Kentucky Electricity Portfolio Model v.2.0 Design Plan

Historical Data Inputs, 1895-2013

Socioeconomic Factors
Gross Domestic Product (GDP)
Educational Achievement
Population
Employment
Public Health
Fuel Prices
Natural Gas Prices
Coal Prices
Petroleum Prices
Weather Data
Temperature
Rainfall
Cooling Degree Days
Heating Degree Days
Policy Options
Portfolio Standards (Min / Max)
Portfolio $CO2_e$ Limits
Portfolio CO2, SO2, NOX, Pricing
Unit-Level Emission Standards
CO2, SO2, HG, NOX, PM



LEGEND
- Complete One-Time Data Transfer
- Annual Data Loop
- Control
- Programming or Statistical Module
- Generating Unit

Unit Parameters
Nameplate Capacity (MW)—Maximum rated full-load output.
Online Year—The year the unit began generating.
Retirement Year—The expected year the unit is to be retired, if already known.
System Life (Years)—Number of years the system is expected to remain in operation beyond the online year.
Capacity Factor (%)—The maximum technically achievable annual output of rated nameplate capacity.
Capital Costs ($ per kW)—Fixed one-time expenses incurred to purchase and install per 1 kilowatt of capacity.
FOM ($ per kW-yr)—Annual Fixed Operations and Maintenance (FOM) costs per kilowatt of install capacity.
VOM ($ per MWh excluding Fuel)—Annual Variable Operations and Maintenance (VOM) per megawatt-hour, excluding fuel and emissions penalties.
Heat Rate (BTU/kWh)— The average annual amount of heat measured in BTU's required to produce one kilowatt-hour of electricity.
Emissions Rates (Lbs per MWh)—The annual average rate of CO_2, NO_x, SO_2, Hg, N_20, CO, and PM emissions in pounds per megawatt-hour.
Lead Time—The number of years required to construct the unit.

Forecast Outputs, 2013-2100

Endogenous Electric Power Factors
Electricity Consumption by Sector
Electricity Prices by Sector
Electricity Expenditures
Electricity Generation by Unit
Electric Power Emissions
Natural Gas Consumption
Coal Consumption
Endogenous Socioeconomic Factors
Gross Domestic Product (GDP)
Per Capita Personal Income
Manufacturing Employment
Retail Employment
Hospitality Employment
Electric Power Employment
Coal Mining Employment
Other Employment
Exogenous Independent Factors
Temperature
Cooling Degree Days
Heating Degree Days
Rainfall
Population
Educational Attainment
Natural Gas Prices
Coal Prices

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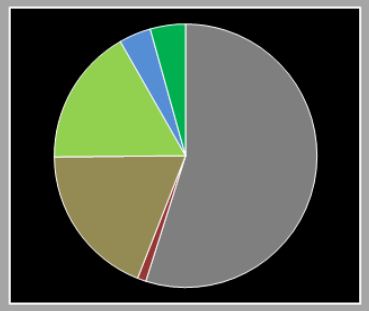
2025 Electricity Portfolio Control Panel

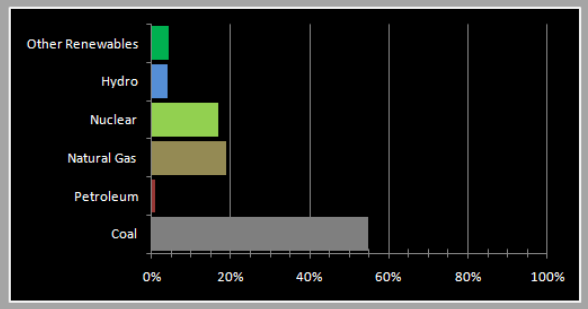
BETA

Summary Scenario Statistics	Year 2025
Total Electricity Rate	$0.0928
Change in Electricity Rate	23.8875%
Change in GHG Emissions	-32.9684%
Model Status	READY

?

Kentucky Total Demand Met: 100.00%
Participating Consumption: 92.12%
Renewables: 8.28%
Qualified Renewables: 5.42%
Alternative Energy: 28.19%
Alternative Energy: 26.83%
Solar Portfolio: 0.49%
Solar Portfolio: 0.53%





Annual Electricity Expenditures: $7,317,154,459.75
Annual Added Costs: $1,441,939,472.40
Kentucky Total Electricity Rate: $0.092776
National Estimate with 95% CI: $0.093801 ($0.0551 ↔ $0.1384)
CO_2e GHG Equivelant: $40.84 per Ton of CO2e

CO2	NOX	SO2	CH4	N20	CO	Particulates
-33.8746%	-27.0835%	-39.9922%	-12.6774%	-15.1773%	-29.2450%	-14.2350%
67,726,666	108,492.29	183,460.99	163,443.35	2,008.3254	54,425.5768	12,353.3196

-32.9684%
71,781,557

Natural Gas	Nuclear	Petroleum	Coal with CCS	Scrubbed Coal	Traditional Coal	All Coal
1,101 $99	147 $103	1,574 $93	$129	2,388 $67	2,187 $33	2,336 $59
18.8958%	16.8639%	1.0600%	0.0000%	40.7216%	14.1815%	54.9031%
114433 MMCF	8 Tons U-235	1975773 BBL		17533479 Tons	6106104 Tons	23639584 Tons
7533 MW	2000 MW	396 MW	Disabled	6091 MW	3782 MW	9874 MW
17,667,858	15,768,000	991,079		38,075,327	13,259,885	51,335,212

Hydroelectric	KY Wind	Imported Wind	Solar	Geothermal	Other Fuel	Efficiency - DSM
23 $90	24 $120	24 $120	230 $267			0 $35
3.9318%	0.0600%	0.0000%	0.4853%	0.0000%	0.0000%	3.0533%
932 MW	32 MW	None	345 MW	Disabled	Disabled	383 ~MWe
3,676,309	56,060	0	453,768			2,854,914

Dairy Cattle	Hog Waste	Poultry Litter	Wood - Direct	Cofired Crops	Crops - Direct	Landfill Gas
-1,399 $99	-1,399 $100	-1,399 $100	99 $100	111 $76	148 $100	-1,398 $47.90
0.0001%	0.0001%	0.0190%	0.4008%	2.4705%	0.7219%	0.1877%
57 Cows	913 Hogs	2956061 Birds	24986 Acres	412029 Acres	120398 Acres	9 Landfills
17 KW	11 KW	2.02 MW	53 MW	329 MW	96 MW	30.3MW
100	100	17,730	374,800	2,310,000	675,000	175,500

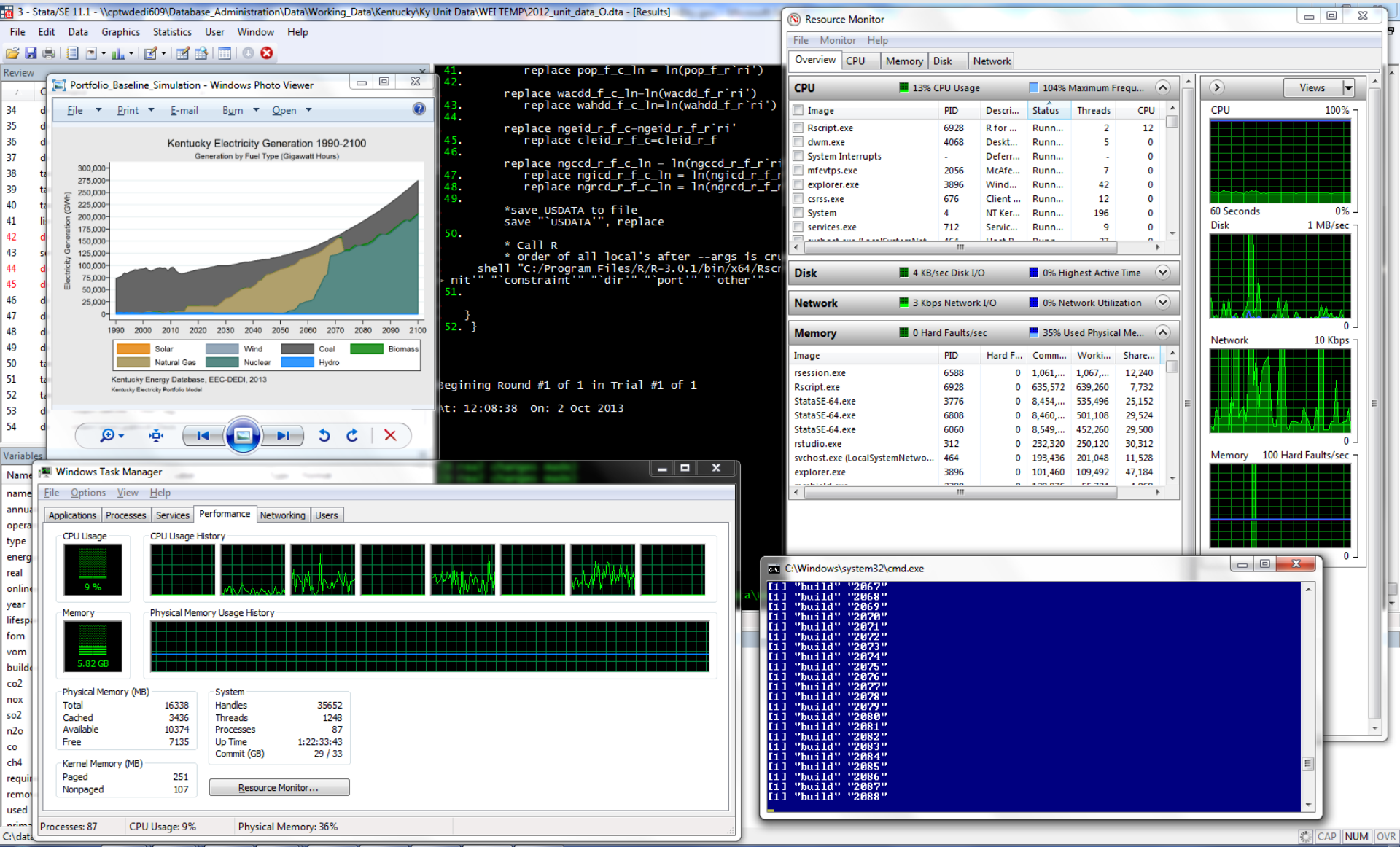
LEC Estimate Source	Demand Scenario	Forecast Method	Demand CAGR	Participation	Per Capita mWh	Independence
DEDI	Moderate Growth	Automatic Forecast	0.831%	92.12%	18.07	80.04%
Edit LEC's	Edit Forecast	Edit Forecast	Edit Forecast	Edit Exemptions	Edit Elasticity	Edit Stuff

Default Portfolios
STATUS QUO
Natural Gas Portfolio | Nuclear Portfolio
Other Button | 12% DSM
REPS Scenario 1 | HB 408

Custom Portfolios
Restore Case 1 | Restore Case 2
Store as Case 1 | Store as Case 2
Restore Case 3 | Restore Case 4
Store as Case 3 | Store as Case 4
Delete Cases and Restore Defaults

Other Options
Basecase | Process Elasticities
Set as Basecase | HELP

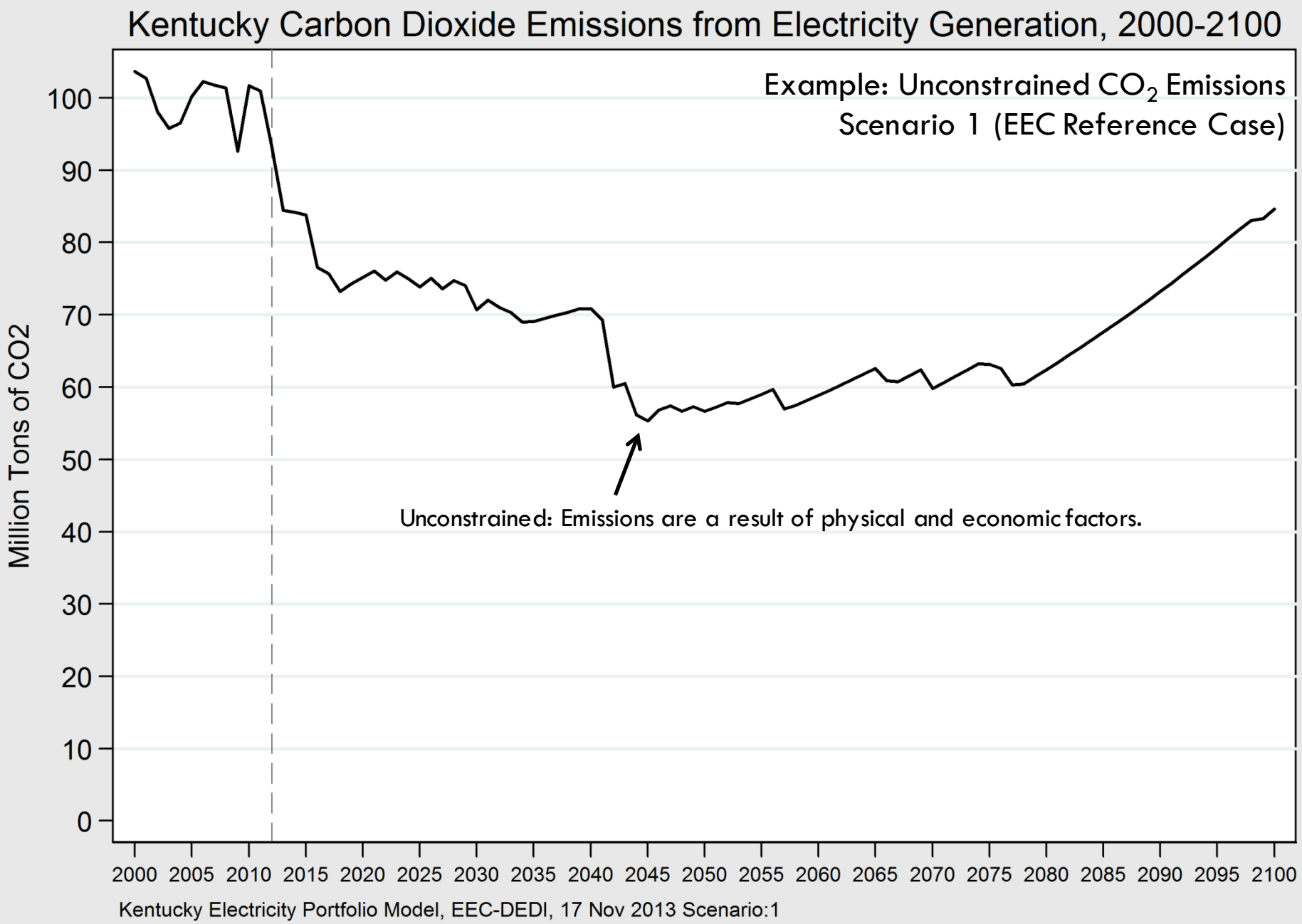
Version 2.0 Behind the Scenes

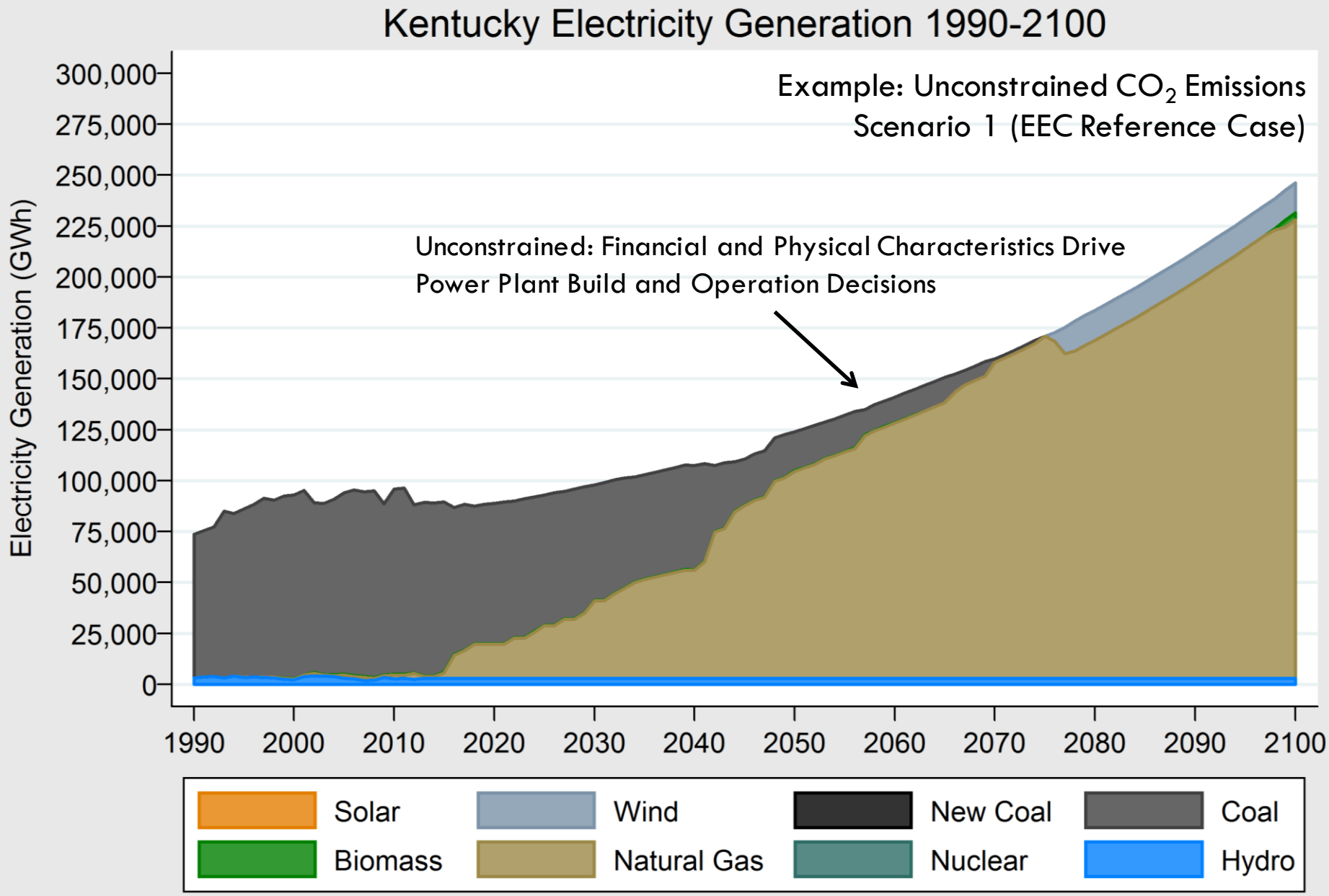


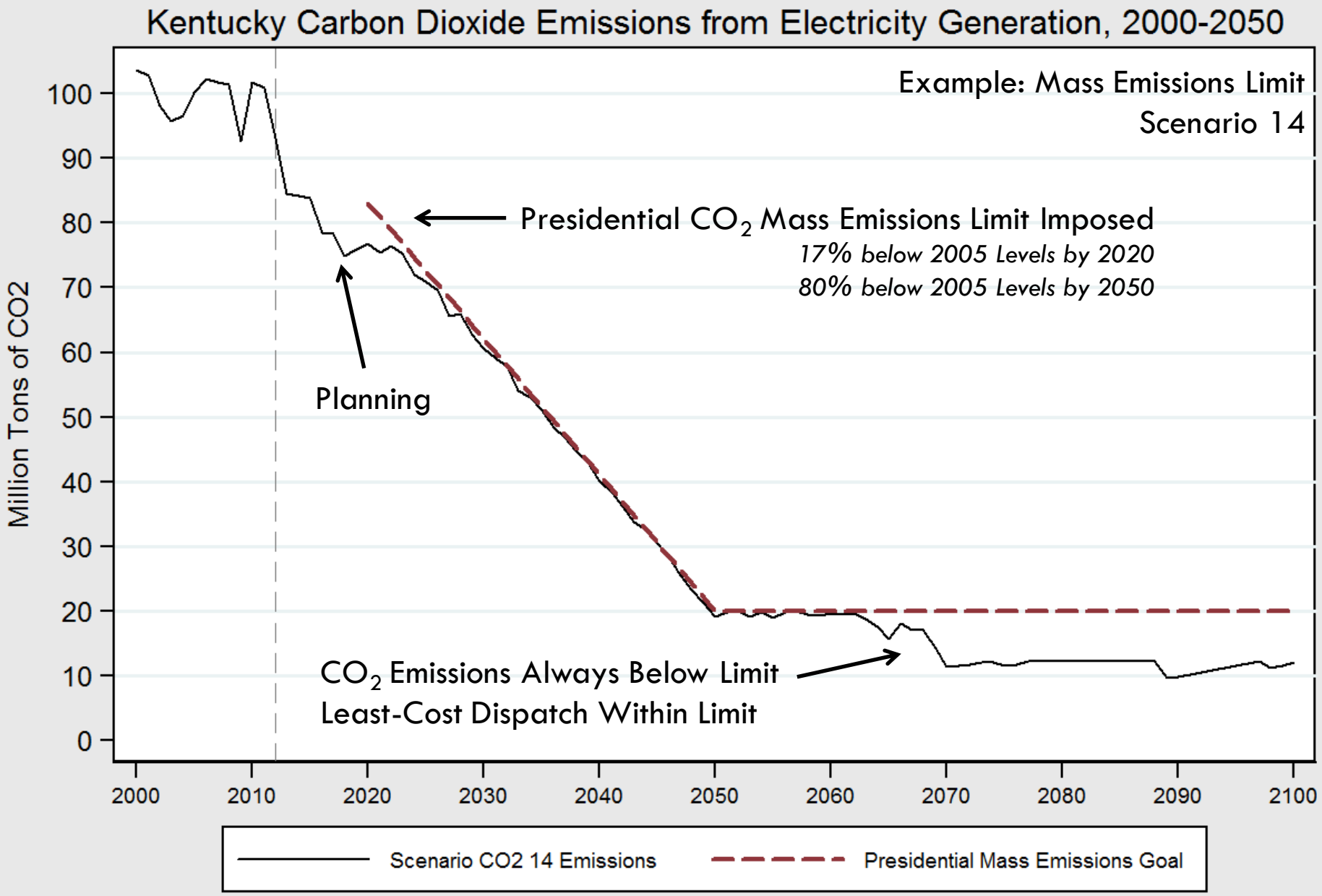
Environmental Regulations

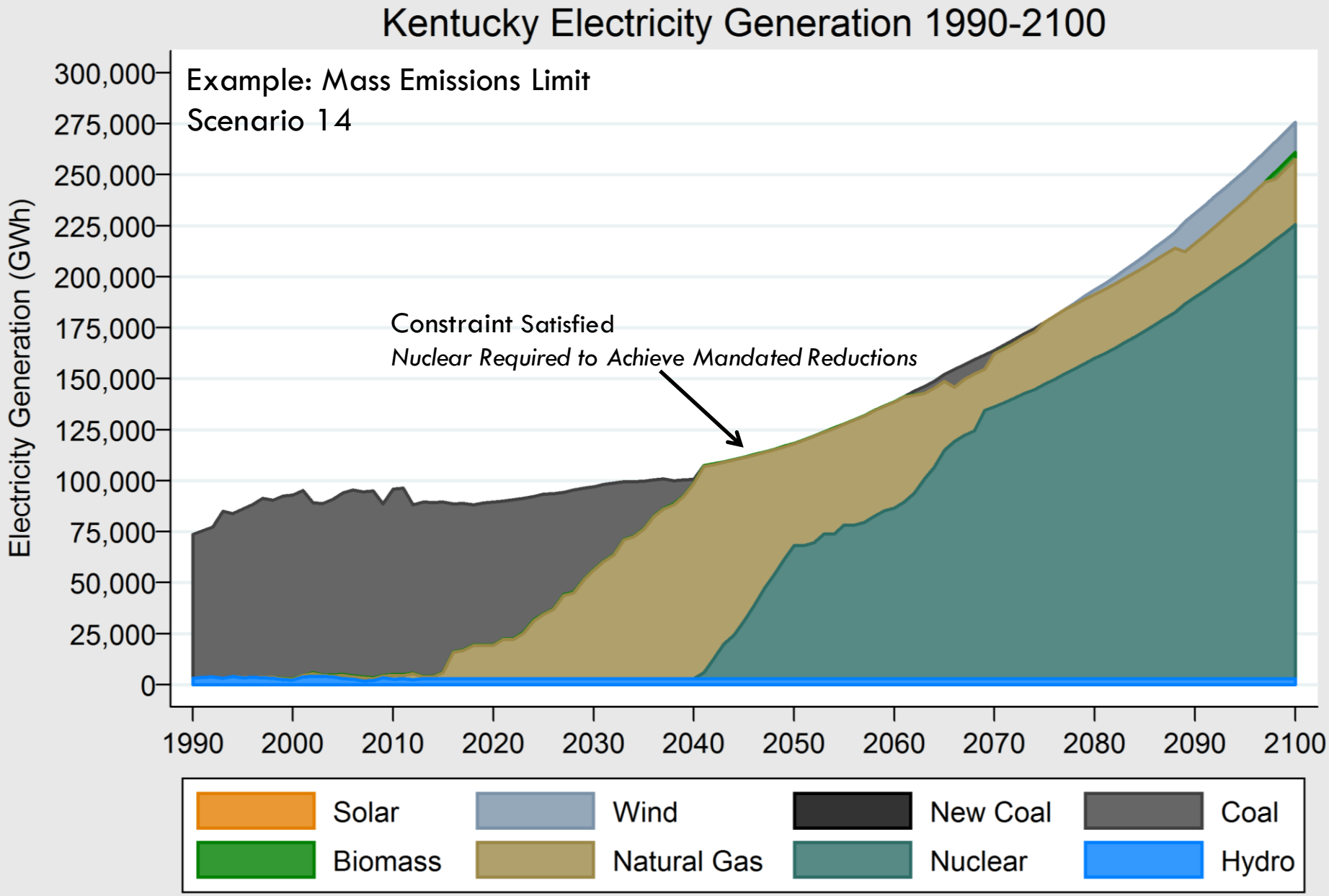
The dispatch optimization algorithm will adhere to any combination of the following types of environmental constraints, which will never be violated or ignored.

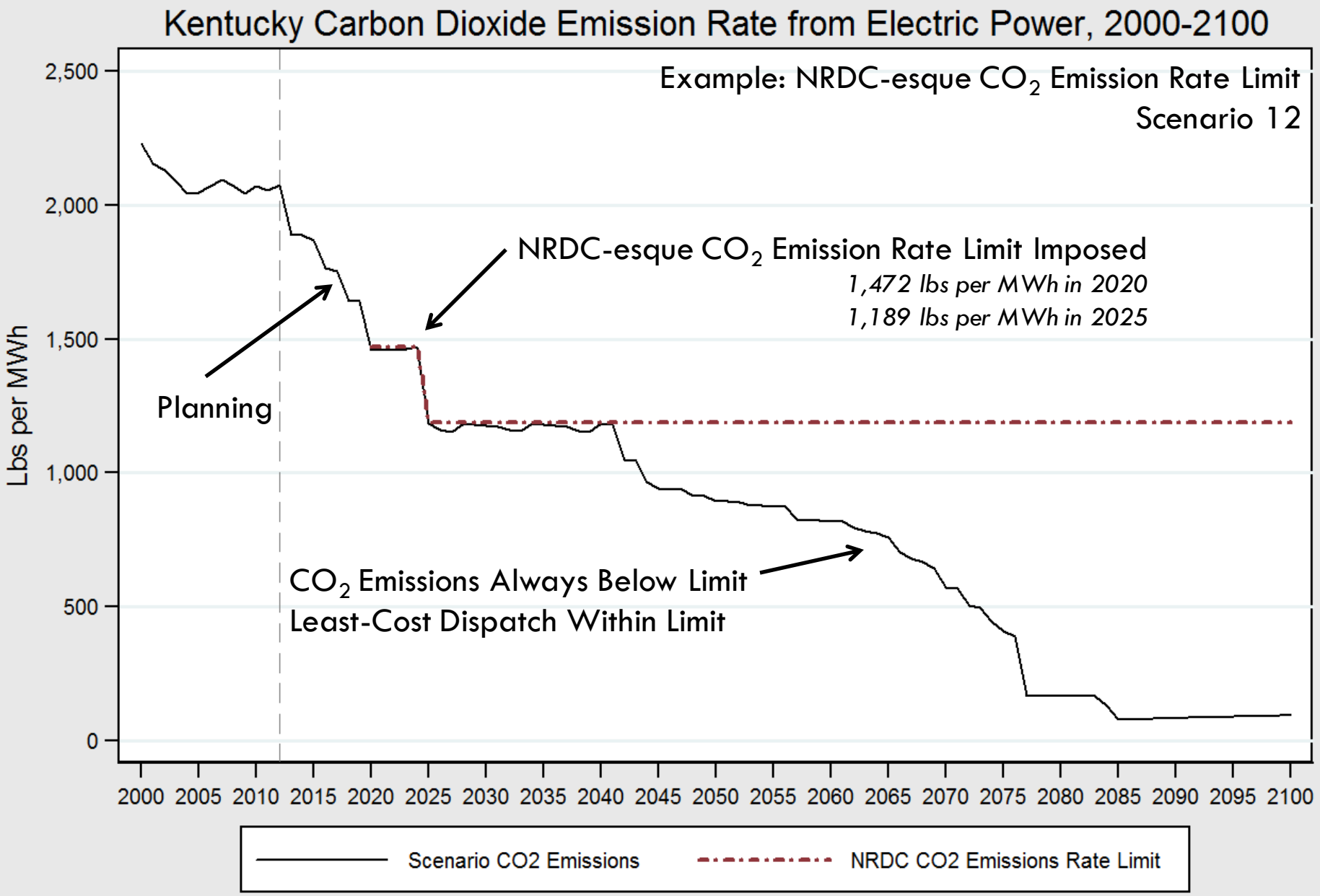
- **Portfolio CO_2 mass emissions limits** can be specified in lbs in any year.
  *When violated, algorithm will achieve compliance by optimizing on **$ per LB of CO_2** reduced.*
- **Portfolio CO_2 emission rate limits** can be specified in **lbs per MWh** in any year.
  *When violated, algorithm will achieve compliance by optimizing on **$ per LB of CO_2** reduced.*
- **Unit-level CO_2, SO_2, and NO_X limits** can be specified in **lbs per MWh** in any year.
  Units in violation will be retired.
- **New Source Performance Standards for CO_2, SO_2, and NO_X limits** in lbs per MWh.
  Units in violation will not be built.
- **CO_2, SO_2, and NO_X fines** can be specified in **$ per lb** in any year.
  Cost of emissions is incorporated into Variable Operations and Maintenance (VOM) costs. The unit will be run if it remains least-cost despite the fine, otherwise the next cheapest technology will be used.

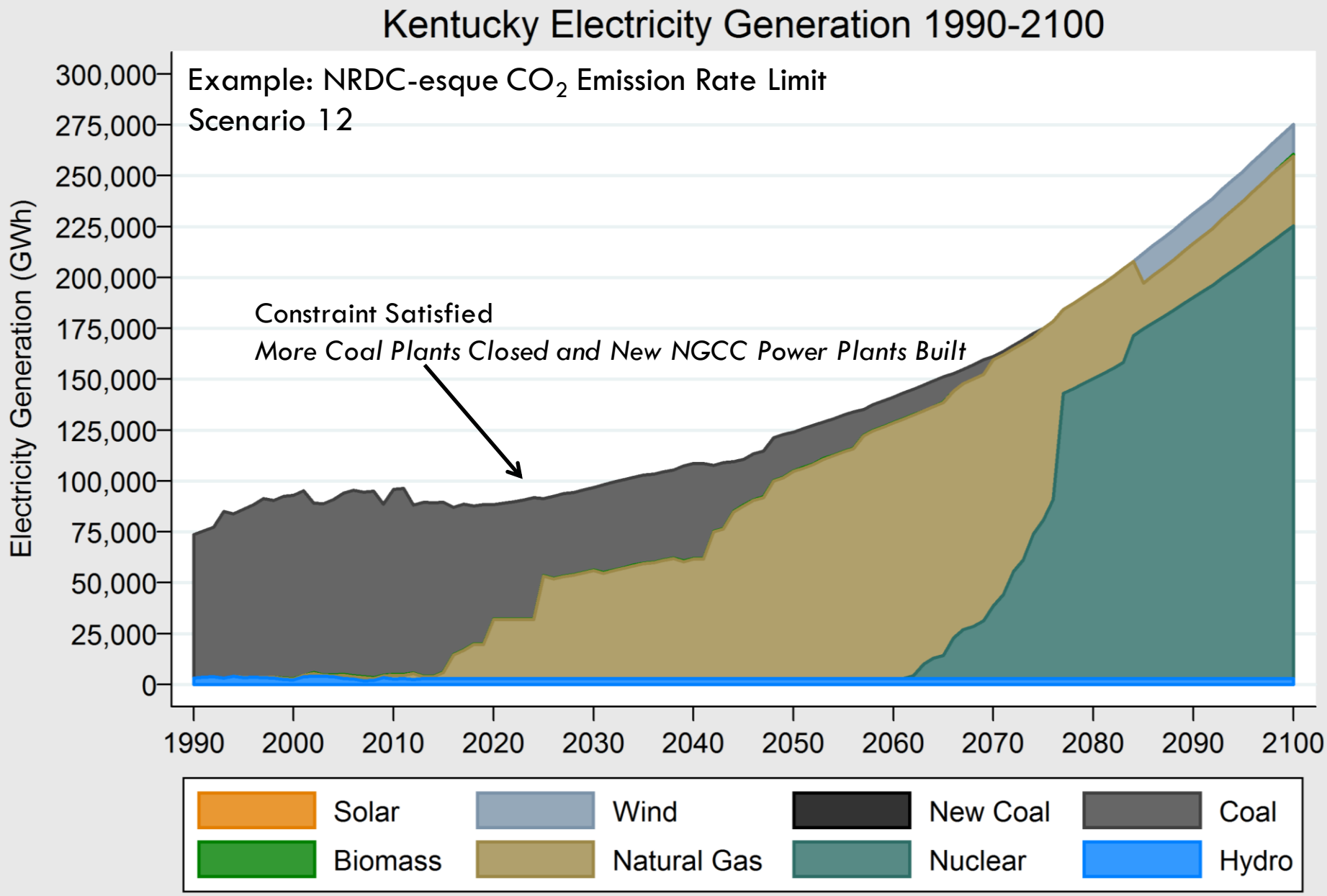

Kentucky Carbon Dioxide Emissions from Electricity Generation, 2000-2100
Example: Unconstrained CO_2 Emissions
Scenario 1 (EEC Reference Case)
Unconstrained: Emissions are a result of physical and economic factors.
Million Tons of CO2
0
10
20
30
40
50
60
70
80
90
100
2000 2005 2010 2015 2020 2025 2030 2035 2040 2045 2050 2055 2060 2065 2070 2075 2080 2085 2090 2095 2100
Kentucky Electricity Portfolio Model, EEC-DEDI, 17 Nov 2013 Scenario:1


Kentucky Electricity Generation 1990-2100
Example: Unconstrained CO_2 Emissions
Scenario 1 (EEC Reference Case)
Unconstrained: Financial and Physical Characteristics Drive
Power Plant Build and Operation Decisions
Electricity Generation (GWh)
300,000
275,000
250,000
225,000
200,000
175,000
150,000
125,000
100,000
75,000
50,000
25,000
0
1990
2000
2010
2020
2030
2040
2050
2060
2070
2080
2090
2100
Solar
Wind
New Coal
Coal
Biomass
Natural Gas
Nuclear
Hydro
Kentucky Electricity Portfolio Model, EEC-DEDI, 17 Nov 2013 Scenario:1


Kentucky Carbon Dioxide Emissions from Electricity Generation, 2000-2050
Example: Mass Emissions Limit
Scenario 14
Presidential CO_2 Mass Emissions Limit Imposed
17% below 2005 Levels by 2020
80% below 2005 Levels by 2050
Planning
CO_2 Emissions Always Below Limit
Least-Cost Dispatch Within Limit
Million Tons of CO2
0
10
20
30
40
50
60
70
80
90
100
2000
2010
2020
2030
2040
2050
2060
2070
2080
2090
2100
Scenario CO2 14 Emissions
Presidential Mass Emissions Goal
Kentucky Electricity Portfolio Model, EEC-DEDI, 26 Nov 2013 Scenario: 14


Kentucky Electricity Generation 1990-2100
Example: Mass Emissions Limit
Scenario 14
Constraint Satisfied
Nuclear Required to Achieve Mandated Reductions
Electricity Generation (GWh)
300,000
275,000
250,000
225,000
200,000
175,000
150,000
125,000
100,000
75,000
50,000
25,000
0
1990
2000
2010
2020
2030
2040
2050
2060
2070
2080
2090
2100
Solar
Wind
New Coal
Coal
Biomass
Natural Gas
Nuclear
Hydro
Kentucky Electricity Portfolio Model, EEC-DEDI, 17 Nov 2013 Scenario:14


Kentucky Carbon Dioxide Emission Rate from Electric Power, 2000-2100
Example: NRDC-esque CO_2 Emission Rate Limit
Scenario 12
NRDC-esque CO_2 Emission Rate Limit Imposed
1,472 lbs per MWh in 2020
1,189 lbs per MWh in 2025
Planning
CO_2 Emissions Always Below Limit
Least-Cost Dispatch Within Limit
Lbs per MWh
2,500
2,000
1,500
1,000
500
0
2000 2005 2010 2015 2020 2025 2030 2035 2040 2045 2050 2055 2060 2065 2070 2075 2080 2085 2090 2095 2100
Scenario CO2 Emissions
NRDC CO2 Emissions Rate Limit
Kentucky Electricity Portfolio Model, EEC-DEDI, 3 Nov 2013, Scenario: 12


Kentucky Electricity Generation 1990-2100
Example: NRDC-esque CO_2 Emission Rate Limit
Scenario 12
Constraint Satisfied
More Coal Plants Closed and New NGCC Power Plants Built
Electricity Generation (GWh)
300,000
275,000
250,000
225,000
200,000
175,000
150,000
125,000
100,000
75,000
50,000
25,000
0
1990
2000
2010
2020
2030
2040
2050
2060
2070
2080
2090
2100
Solar
Wind
New Coal
Coal
Biomass
Natural Gas
Nuclear
Hydro
Kentucky Electricity Portfolio Model, EEC-DEDI, 17 Nov 2013 Scenario:12

Portfolio Standards

The dispatch model algorithm has a versatile set of portfolio standard options, designed to process most types of portfolio standards. The algorithm will search for the least-cost portfolio that satisfies the portfolio standard.

- **Staff can specify a "category"** and determine what types of generation are part of this category. An example of a category could be "renewables" or "coal".

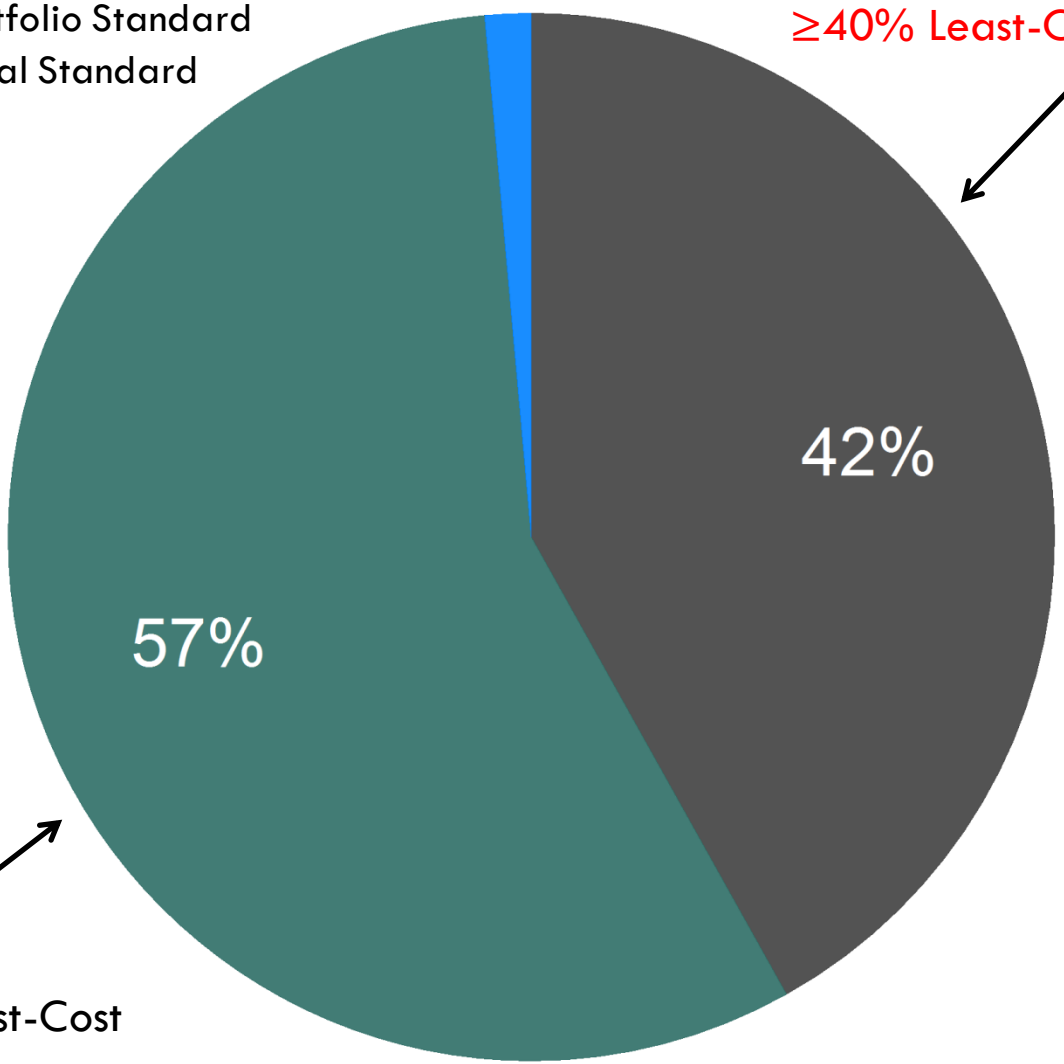
- **A category minimum portfolio standard** can be specified in MWh and/or as a percentage of total generation in every year.

- **A category maximum portfolio standard** can be specified in MWh and/or as a percentage of total generation in every year.

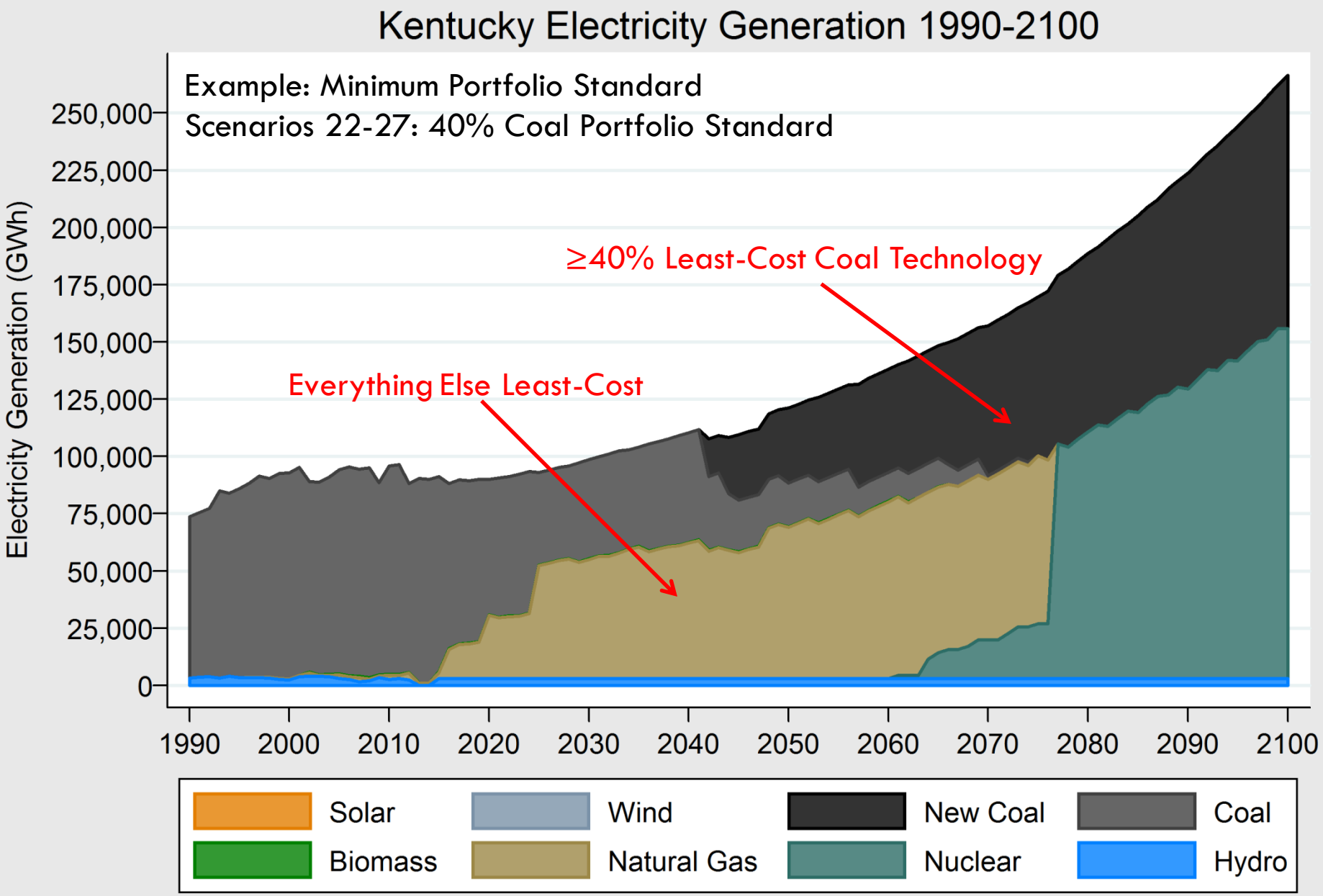
- Unlike Version 1.0 of the Portfolio Model, where the user specified exactly how electricity would be generated by optimizing within constraints, Version 2.0 more realistically mimics real world market dynamics.

Kentucky Electricity Generation, 2085

Example: Minimum Portfolio Standard
Scenarios 26: 40% Coal Standard



Kentucky Electricity Portfolio Model, EEC-DEDI, 1 Nov 2013 Scenario:26



Kentucky Electricity Portfolio Model, EEC-DEDI, 25 Apr 2014 Scenario:26

Hierarchical Constraints

The dispatch model algorithm has a variety of complex and potentially conflicting user-specified constraints.

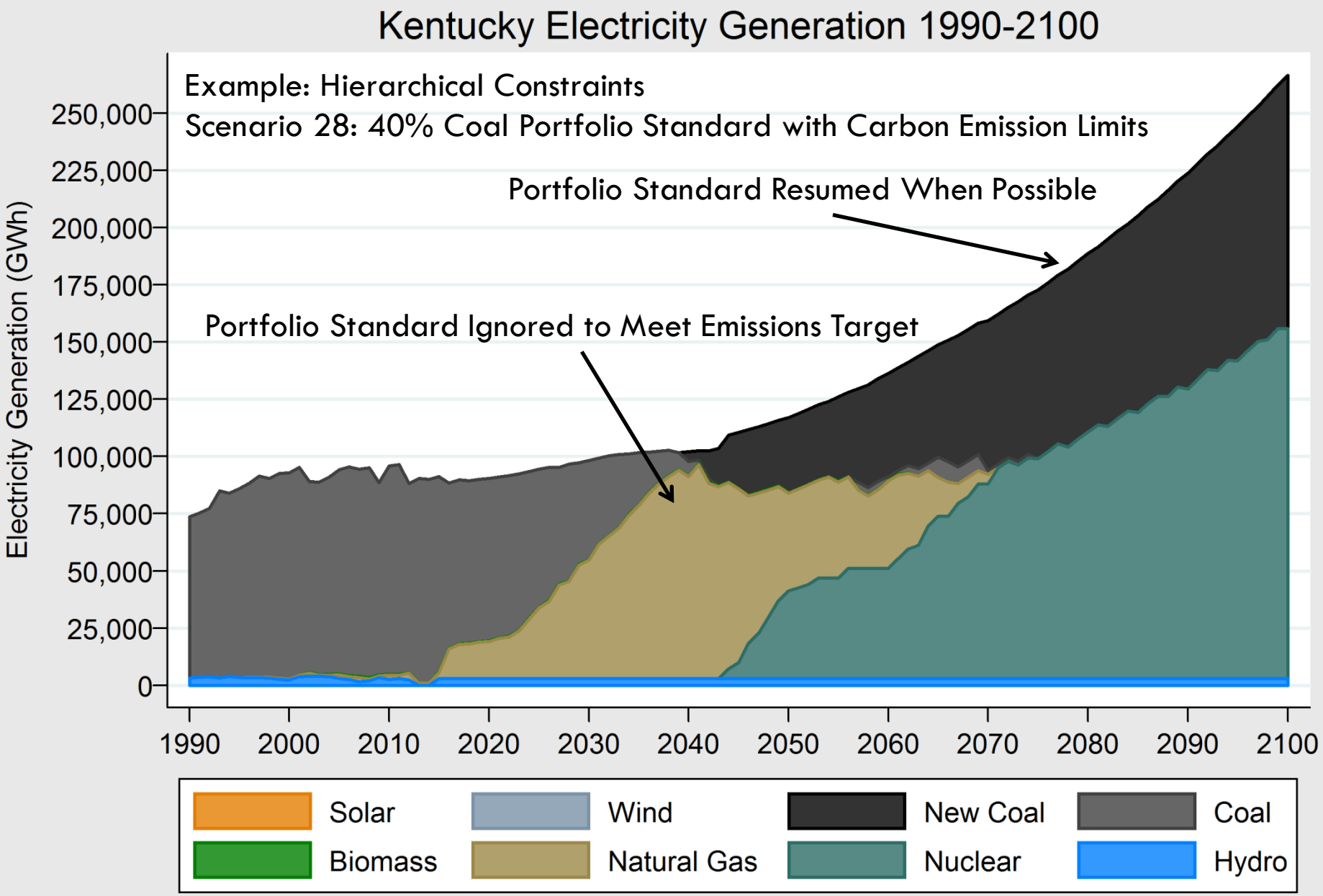
1. **Physical resource and technology limitations** define the parameters of what is possible.

2. **Environmental regulations,** including portfolio carbon dioxide emission rate or mass limits or unit-level CO_2, SO_2, or NO_X limits will not be violated, regardless of costs or implications.

3. **Electricity demand** will be met so long as there are resources to do so without violating environmental constraints.

4. **Portfolio Standards** will be adhered to so long as they are physically possible and do not violate environmental regulations. Portfolio standards that conflict with environmental constraints, or that are not achievable will be ignored.

5. **Least-cost** electricity will be delivered while above constraints are satisfied.


Kentucky Electricity Generation 1990-2100
Example: Hierarchical Constraints
Scenario 28: 40% Coal Portfolio Standard with Carbon Emission Limits
Portfolio Standard Resumed When Possible
Portfolio Standard Ignored to Meet Emissions Target
Electricity Generation (GWh)
250,000
225,000
200,000
175,000
150,000
125,000
100,000
75,000
50,000
25,000
0
1990
2000
2010
2020
2030
2040
2050
2060
2070
2080
2090
2100
Solar
Wind
New Coal
Coal
Biomass
Natural Gas
Nuclear
Hydro
Kentucky Electricity Portfolio Model, EEC-DEDI, 25 Apr 2014 Scenario:28

Unit Retirements

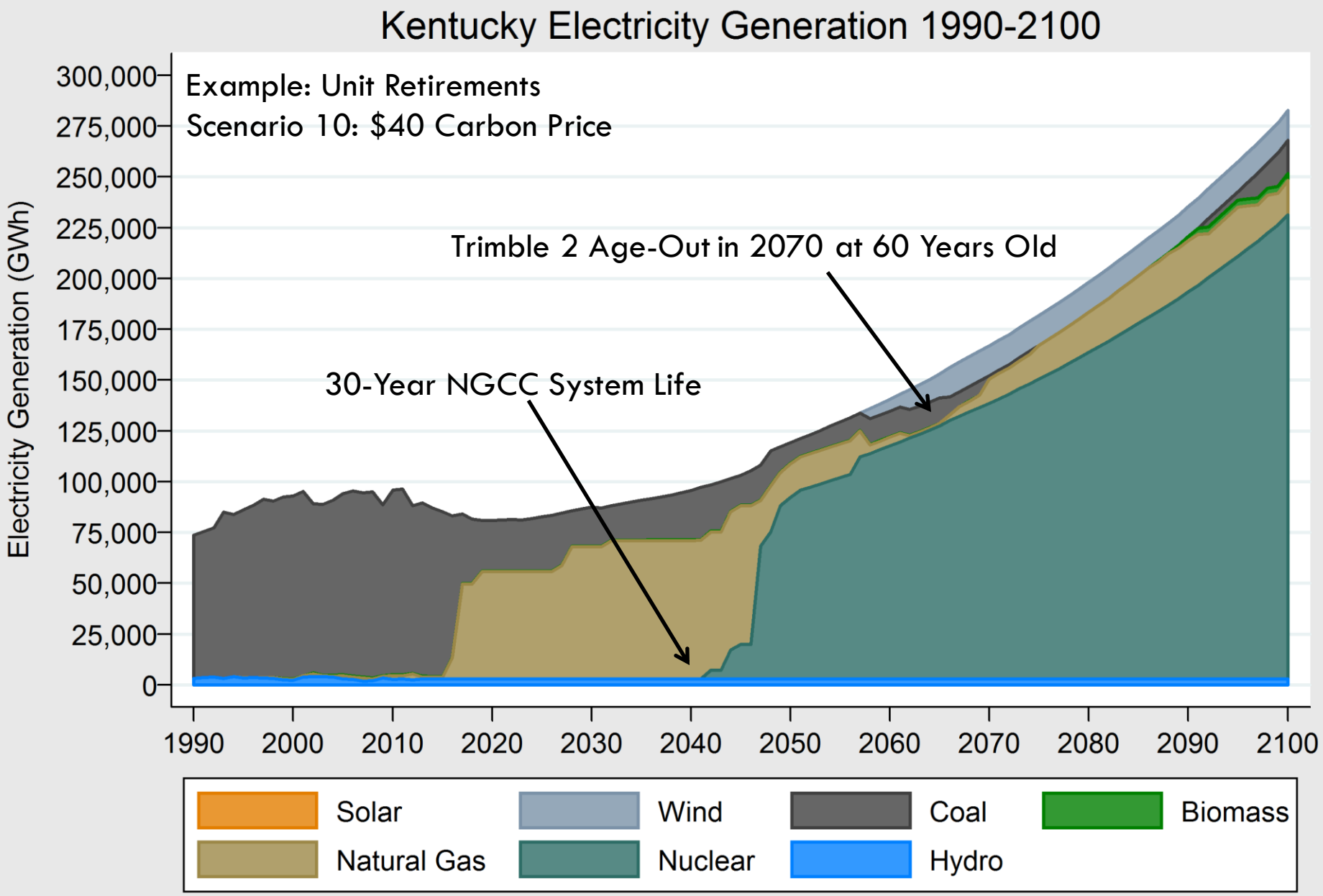
The dispatch algorithm can autonomously choose to retire existing and future electricity generation units for one or more of the four following reasons.

1. **Environmental retirements** occur when the unit's individual emissions of a criteria pollutant violate the maximum allowable emissions rates or when shutting off the unit is the least-cost means of complying with a portfolio-wide CO2 emissions standard.

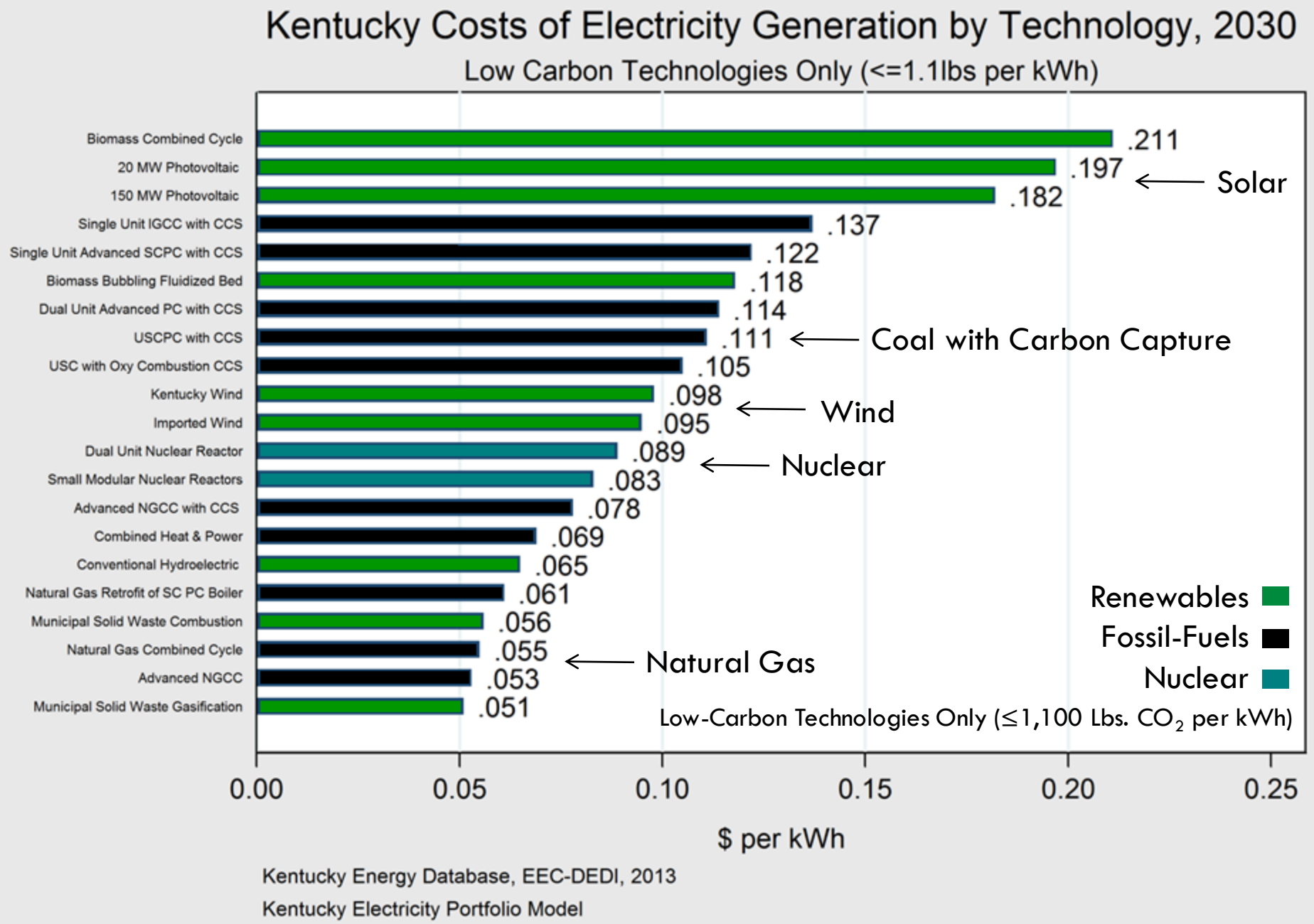
2. **Economic retirements** occur when the total costs of continuing to operate a generating asset are higher than the costs of abandoning the asset, including the capital invested into it, and building and operating a suitable replacement. An economic retirement can also occur if the unit is no-longer needed to generate electricity.

3. **Age-out retirements** occur when the unit has exhausted its usable system life as specified in its physical characteristics.

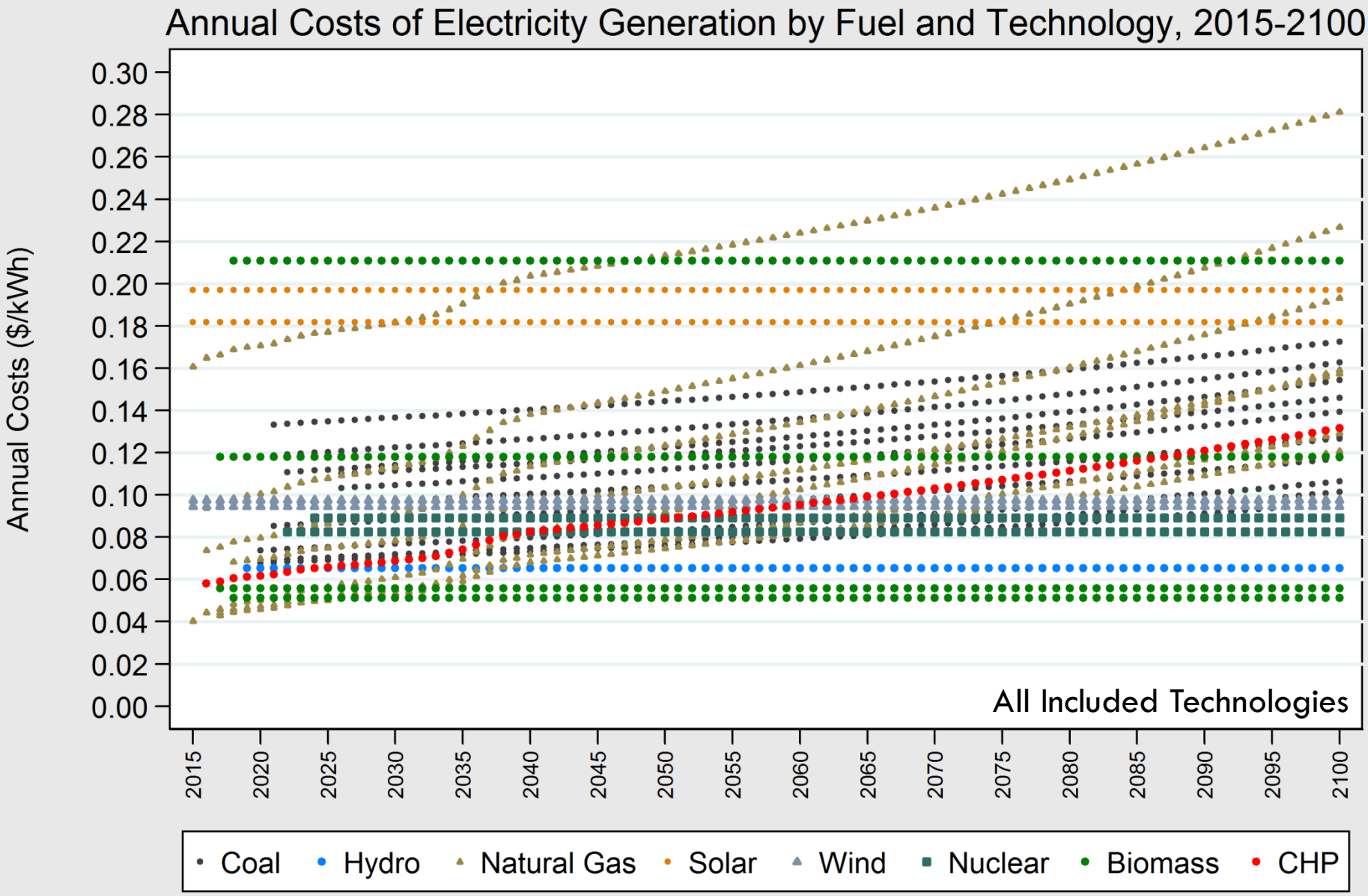
4. **Staff-specified retirements** occur when the planned date that a particular unit will go offline has already been made known to staff, either publically or confidentially, by the owner or government regulator of the asset.



Kentucky Electricity Portfolio Model, EEC-DEDI, 1 Nov 2013 Scenario:10



Detailed Cost Data Available on Pages C.89 and C.90 of Complete Report



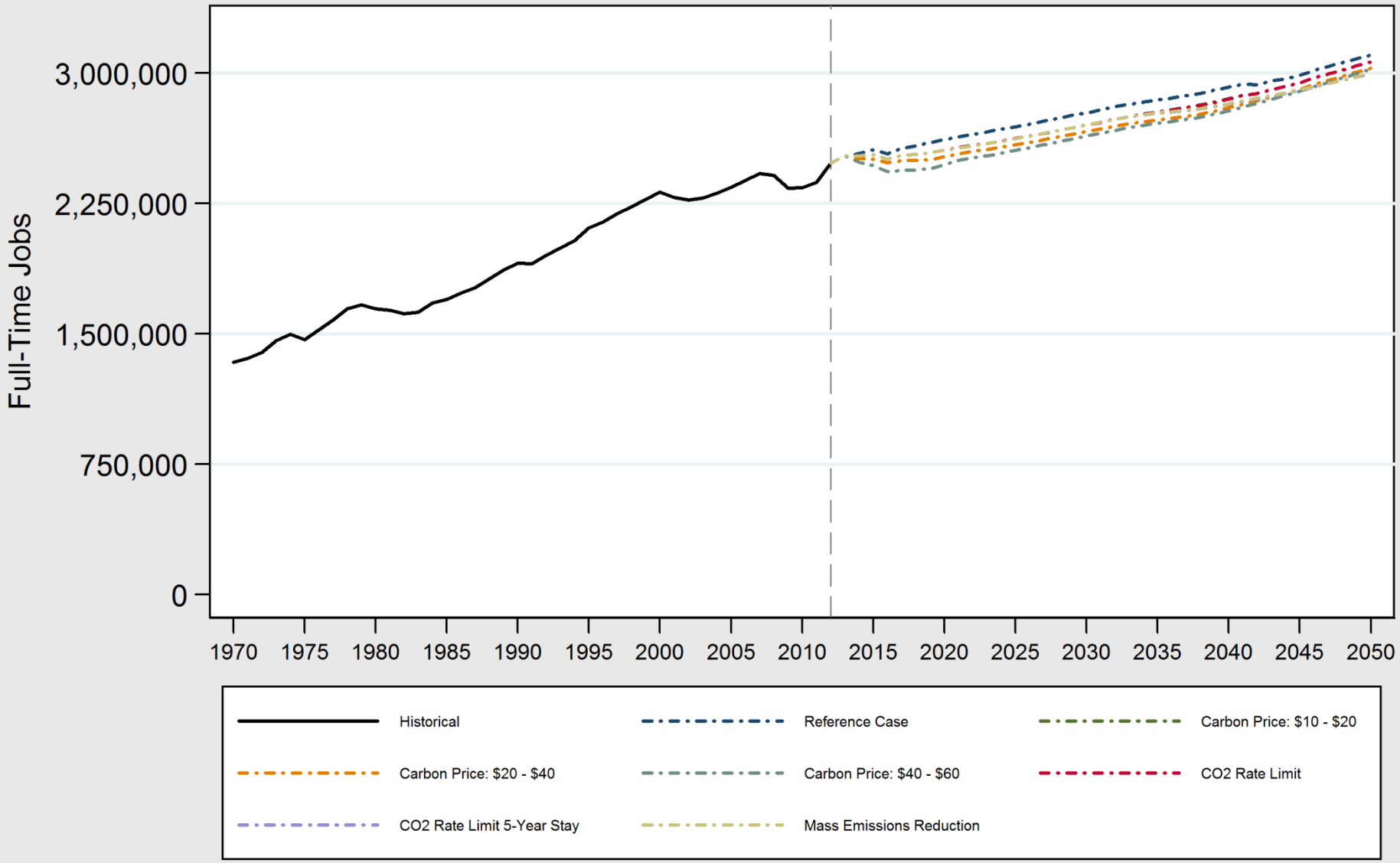
Kentucky Energy Database, EEC-DEDI, 2013

Kentucky Electricity Portfolio Model

Technology	2030 Cost ($ per kWh)	Primary Fuel	Nameplate (MW)	Capacity Factor	$ / kW	$ / kW-yr	$ / MWh	System Life	Heat Rate	Lead Time (Years)	CO_2 (lb./MWh)	NO_x (lb./MWh)	SO_2 (lb./MWh)
Biomass Combined Cycle	$0.21079	Biomass	20	0.83	8180	356.07	17.49	30	12350	5	0	0.09	0
20 MW Photovoltaic	$0.19691	Solar	20	0.25	4183	27.75	0	30	0	2	0	0.01	0
150 MW Photovoltaic	$0.18186	Solar	150	0.25	3873	24.69	0	30	0	2	0	0.01	0
Fuel Cells	$0.18170	Natural Gas	10	0.9	7108	0	43	30	9500	2	1235	0.1235	0.00124
Single Unit IGCC with CCS	$0.13668	Coal	520	0.83	6599	72.83	8.45	30	10700	7.5	220	0.08025	0.1605
Single Unit Advanced SCPC with CCS	$0.12244	Coal	650	0.85	5227	80.53	9.51	30	12000	7.5	247	0.72	0.24
Biomass Bubbling Fluidized Bed	$0.11795	Biomass	50	0.78	4114	105.63	5.26	30	13500	3.5	0	1.08	0
Dual Unit Advanced PC with CCS	$0.11403	Coal	1300	0.85	4724	66.43	9.51	30	12000	9	247	0.72	0.24
Combustion Turbine	$0.11308	Natural Gas	85	0.3	973	7.34	15.45	30	10850	3	1269	0.3255	0.01085
USCPC with CCS	$0.11145	Coal	550	0.85	5130	47.3	9.2	30	10270	12.5	205	0.7189	0.00001
USC with Oxy Combustion CCS	$0.10469	Coal	550	0.85	4770	45.55	7.1	30	10353	12.5	135	0.72471	0.21741
Single Unit IGCC	$0.09752	Coal	600	0.85	4400	62.25	7.22	30	8700	6.5	1792	0.065	0.2175
Imported Wind	$0.09468	Wind	30	0.34	2513	39.55	0	30	0	2	0	0.01	0
Advanced Combustion Turbine	$0.09100	Natural Gas	210	0.3	676	7.04	10.37	30	9750	3	1141	0.2925	0.00975
Dual Unit Nuclear Reactor	$0.08915	Uranium	2234	0.9	5530	93.28	2.14	30	10452	11	0	0.01	0
Dual Unit IGCC	$0.08809	Coal	1200	0.85	3784	51.39	7.22	30	8700	8	1792	0.065	0.2175
Small Modular Nuclear Reactors	$0.08267	Uranium	180	0.9	5000	93.28	2.14	30	10452	9	0	0.01	0
Advanced NGCC with CCS	$0.07846	Natural Gas	340	0.87	2095	31.79	6.78	30	7525	5	90	0.05644	0.00753
Single Unit Advanced SCPC	$0.07683	Coal	650	0.85	3246	37.8	4.47	30	8800	6.5	1813	0.528	0.88
USCPC with 20% Biomass	$0.07345	Cofire	650	0.85	3147	31.18	4.47	30	8800	6.5	1496	0.53	0.88
Dual Unit Advanced SCPC	$0.07190	Coal	1300	0.85	2934	31.18	4.47	30	8800	8	1813	0.528	0.88
Ultra-Supercritical PC	$0.07060	Coal	550	0.85	3000	34.16	5.2	30	7654	6.5	1554	0.53578	0.65824
Combined Heat & Power	$0.06864	Natural Gas	10	0.87	2278	7.5	6.1	30	6007	2.5	364	0.1802	0.006
Conventional Hydroelectric	$0.06528	Hydro	10	0.52	2936	14.13	0	30	0	6	0	0	0
Natural Gas Retrofit of SC PC Boiler	$0.06101	Natural Gas	250	0.87	250	25	3.6	30	9355	2	1095	0.28065	0
Municipal Solid Waste Combustion	$0.05587	LFG	20	0.85	4001	97.1	-9	30	18000	3.5	0	4.86	1.26
Natural Gas Combined Cycle	$0.05534	Natural Gas	620	0.87	917	13.17	3.6	30	7050	3.5	825	0.05288	0.00705
Advanced NGCC	$0.05327	Natural Gas	400	0.87	1023	15.37	3.27	30	6430	3.5	752	0.04823	0.0064
Municipal Solid Waste Gasification	$0.05118	LFG	27	0.85	3784	90.5	-10	30	13600	5	0	3.67	0.952
USCPC with 20% Biomass - Retrofit	$0.03230	Cofire	650	0.85	213	1.06	0.45	30	10600	2	1802	0.64	1.06

Kentucky Employment Forecast, 1970-2050

Nuclear Banned Portfolio



Kentucky Electricity Portfolio Model, EEC-DEDI, 11 Nov 2013

Change in Employment, 2035
(Full Time Jobs)

Federal Policy Options	Portfolios			
	1: Nuclear Banned	2: Nuclear Allowed	3: Balanced Portfolio	4: Coal Portfolio
1: Reference Case	0	0	0	0
2: Carbon Price: $10 - $20	-60,000	-60,000	-60,000	-70,000
3: Carbon Price: $20 - $40	-110,000	-110,000	-110,000	-130,000
4: Carbon Price: $40 -$60	-130,000	-130,000	-130,000	-170,000
5: CO2 Rate Limit	-70,000	0	0	NA
6: Presidential CO2 Rate Limit	-70,000	-20,000	-40,000	NA
7: Mass Emissions Reduction	-70,000	-30,000	-40,000	NA

Change in Employment, 2035
(Percent)

Federal Policy Options	Portfolios			
	1: Nuclear Banned	2: Nuclear Allowed	3: Balanced Portfolio	4: Coal Portfolio
1: Reference Case	0.00%	0.00%	0.00%	0.00%
2: Carbon Price: $10 - $20	-2.11%	-2.11%	-2.11%	-2.45%
3: Carbon Price: $20 - $40	-3.87%	-3.87%	-3.87%	-4.55%
4: Carbon Price: $40 -$60	-4.58%	-4.58%	-4.58%	-5.94%
5: CO2 Rate Limit	-2.46%	0.00%	0.00%	NA
6: Presidential CO2 Rate Limit	-2.46%	-0.70%	-1.41%	NA
7: Mass Emissions Reduction	-2.46%	-1.06%	-1.41%	NA

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